VELOCITY STATISTICS AND SPECTRA IN THREE-STREAM JETS

Tobias Ecker
K. Todd Lowe
Wing F. Ng
Virginia Tech

Brenda Henderson
NASA Glenn Research Center

Stewart Leib
Ohio Aerospace Institute

AIAA SciTech 2016

Virginia Tech Center for Renewable Energy and Aerodynamic Testing

Overview

- **Background**
- **Time-resolved Doppler Global Velocimetry**
- **Facility and experiment**
- **Turbulence results**
- **Conclusions and next steps**

Acknowledgements:

This work supported by Commercial Supersonic Technology Project in the Advanced Air Vehicles Program and the US Office of Naval Research (ONR) through the Hot Jet Noise Basic Research Challenge

Mark Wernet for PIV data and support in planning and setup

Motivation

Persistent Jet Noise Challenge

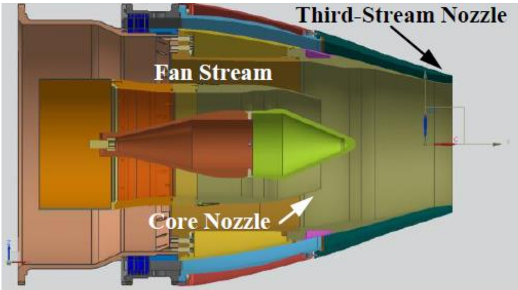
- Supersonic transport unique jet noise problems
- Substantial impact on health of service persons

Instrument development goals

- New tools for turbulent plume details
- Data for development of models for jet noise prediction

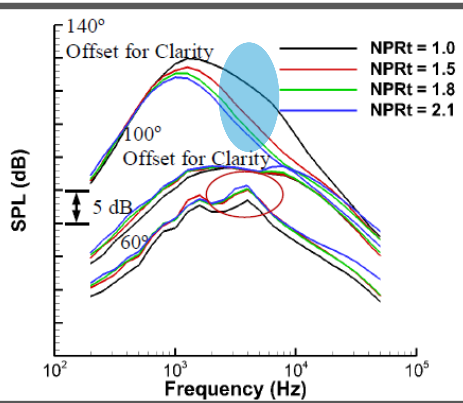
Continuous dB	Permissible Exposure Time
85 dB	8 Hours
88 dB	4 hours
91 dB	2 hours
94 dB	1 hour
97 dB	30 minutes
100 dB	15 minutes
103 dB	7.5 minutes
106 dB	3.75 minutes (< 4 min)
109 dB	1.875 minutes (< 2 min)
112 dB	.9375 min (~ 1 min)
115 dB	.46875 min (~ 30 sec)

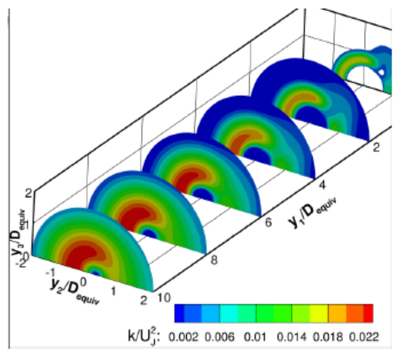
Background



Henderson (2012): Axisymmetric third stream:

- High frequency noise reduction
- Reduced impact with forward flight



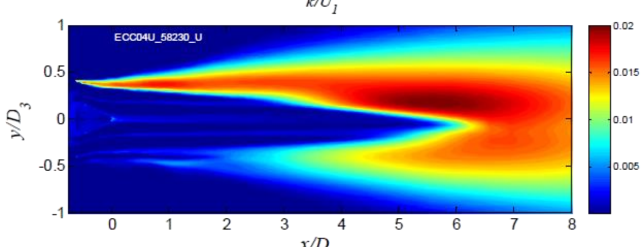


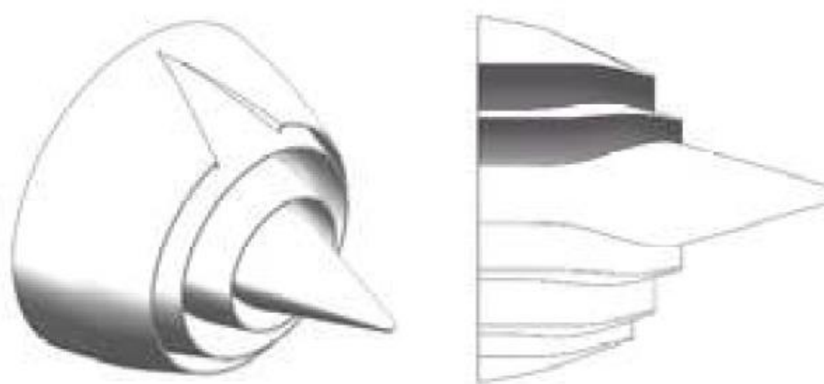
Henderson, Leib and Wernet (2015): *Asymmetric* third stream

- Dramatic reductions downstream
- Redistribution of TKE

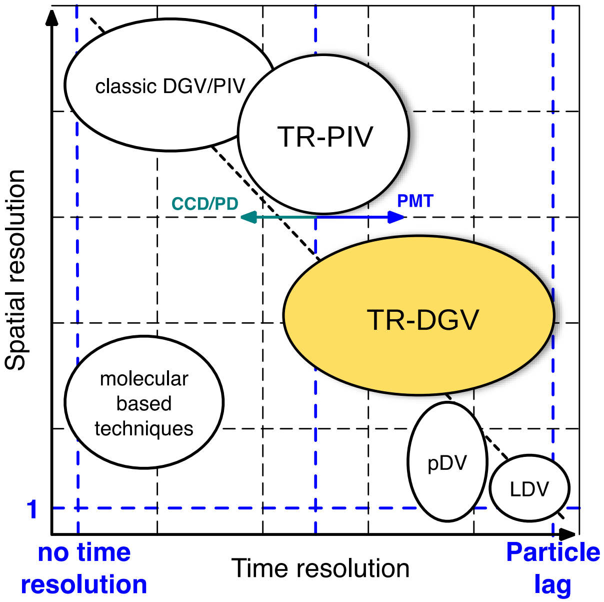
Papamoschou et al. (2016): Even more creative third streams:

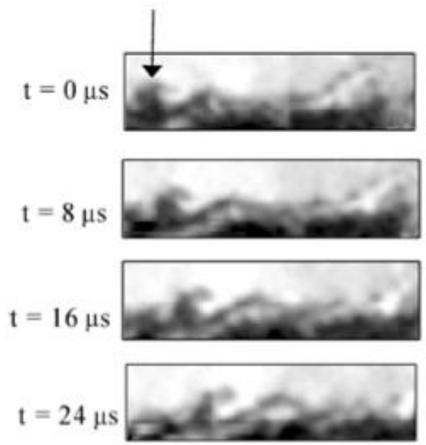
- RANS shows redistribution of TKE
- Dramatic noise downstream reduction





High speed jet instrumentation & measurements





High-data rate, non-intrusive measurements in **cold supersonic jets/ hot subsonic jets**:

- LDV, Kerhervé et al. (EIF 2004)
  - 2-point LDV in cold supersonic jet
  - Space-time correlations
- TR-PIV, Wernet and Bridges (2007)
  - Up to 50 kHz in subsonic hot jets
  - Spectral development
  - Space-time correlations
- Megaherz rate DGV (Thurow et al.,2005):
  - max. 1 MHz camera sampling rate (presented results up to 250 kHz), 1-comp
  - Supersonic cold jet
  - Convective velocities

Thurow, B., JIANG, N., Lempert, W., & Samimy, M. (2005). Development of megahertz-rate planar doppler velocimetry for high-speed flows. AIAA Journal

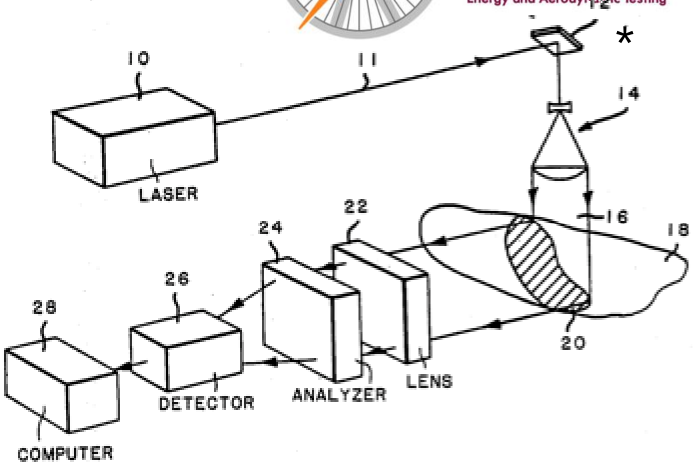
Doppler Global Velocimetry

Basics:

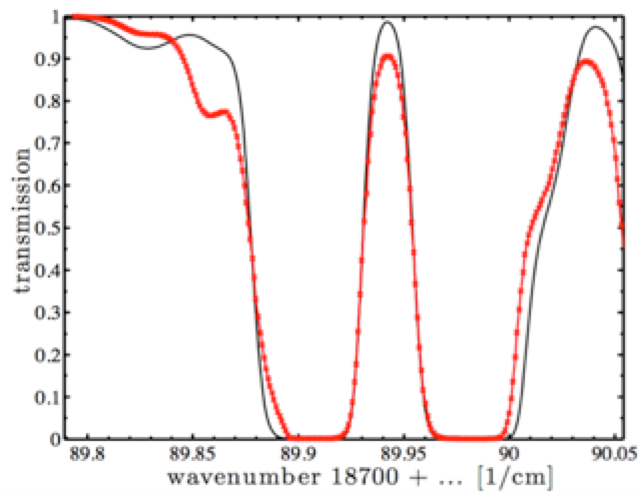
- First developed by Komine (Northrop Co) in 1990, refined by Meyers and Komine (1991)
- Mie scattered light is sent trough a molecular gas cell (e.g Iodine) and its frequency transduced to intensity (24 “optical frequency-to-intensity converter”)
- Using a reference or calibration the Doppler frequency shift can be determined:

$$f_D = \frac{\vec{o} - \vec{i}}{\lambda} \cdot \vec{V}$$

- Considered to be optimal for high speed flow due to absolute error
- Conventional systems have (mean) uncertainties in the range $\pm 0.5 m/s$ to $\pm 3 m/s$

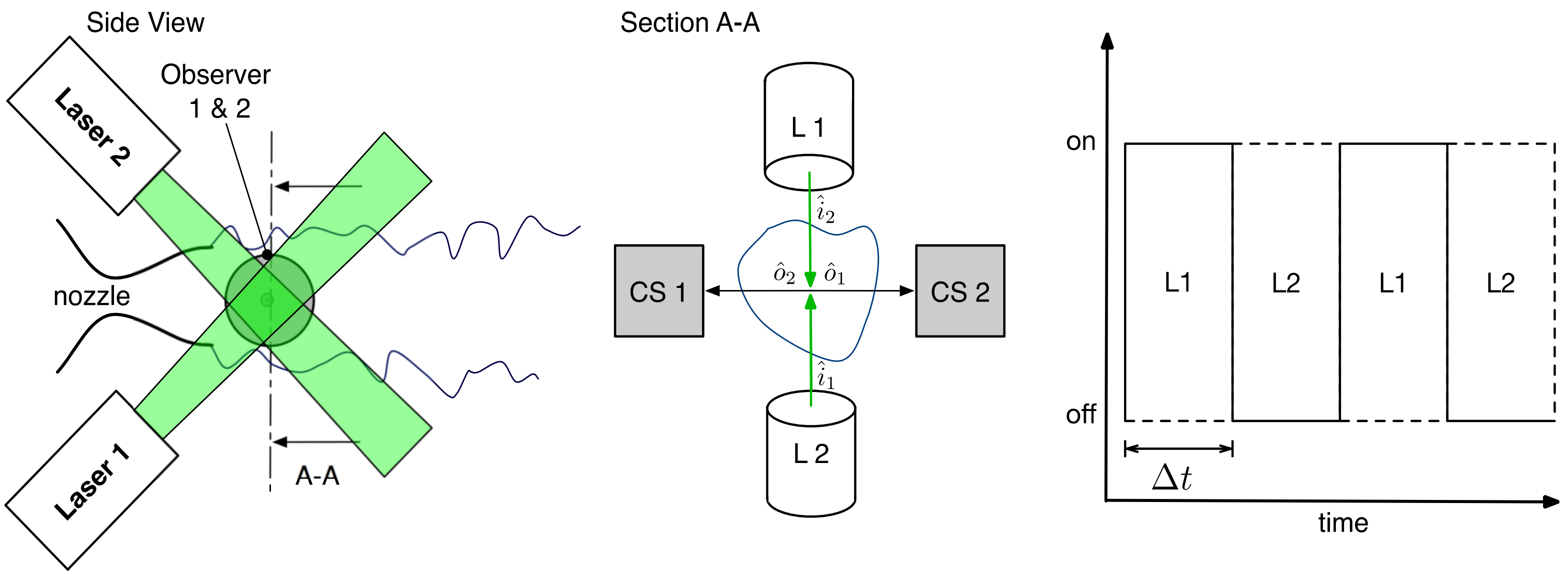


*Komine, System for measuring velocity field of fluid flow utilizing a laser-Doppler spectral image converter, US Patent No. 4 919 536, 1990



Iodine cell transmission scan

Time-resolved Doppler Global Velocimetry



$$f_D = \frac{\vec{o} - \vec{i}}{\lambda} \cdot \vec{V}$$

Three-velocity component operation by velocity multiplexing:

2 laser beam directions + 2 collection directions = 3 linearly independent Doppler directions + 1 redundant measurement

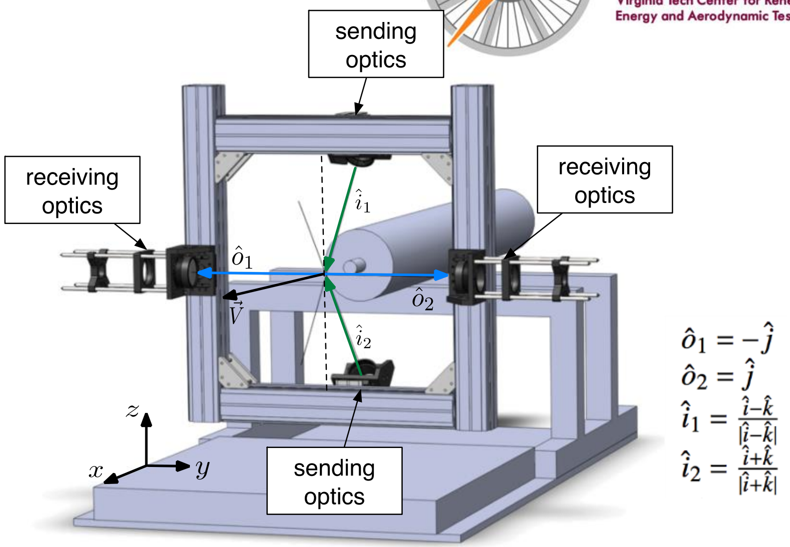
Previous TR-DGV

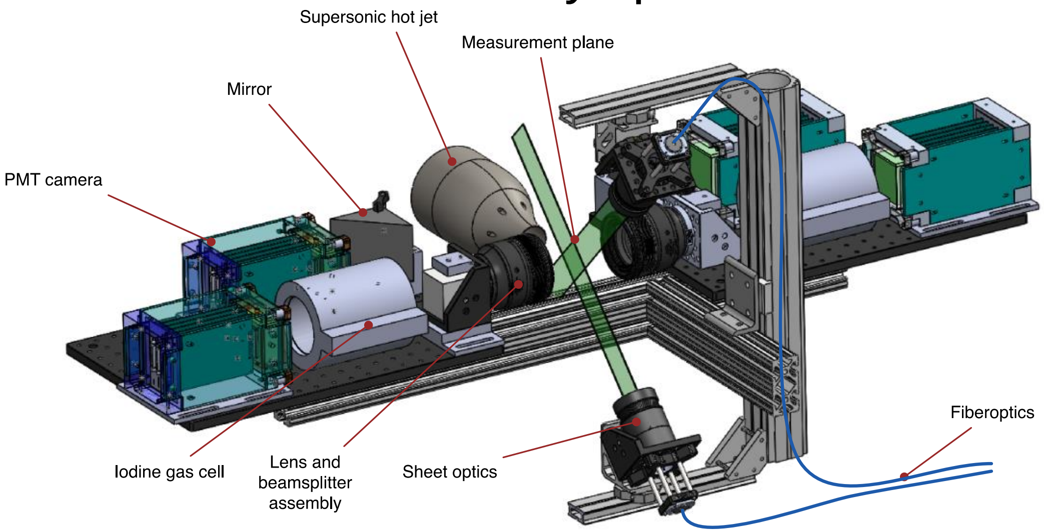
Thurow et al. (2005)

- High-Speed camera based

Ecker et al. (2014)

- Single point 3 component TR-DGV (PMT based)
- First approach to laser beam multiplexing
- Mean velocity, Reynolds shear stresses and velocity spectra

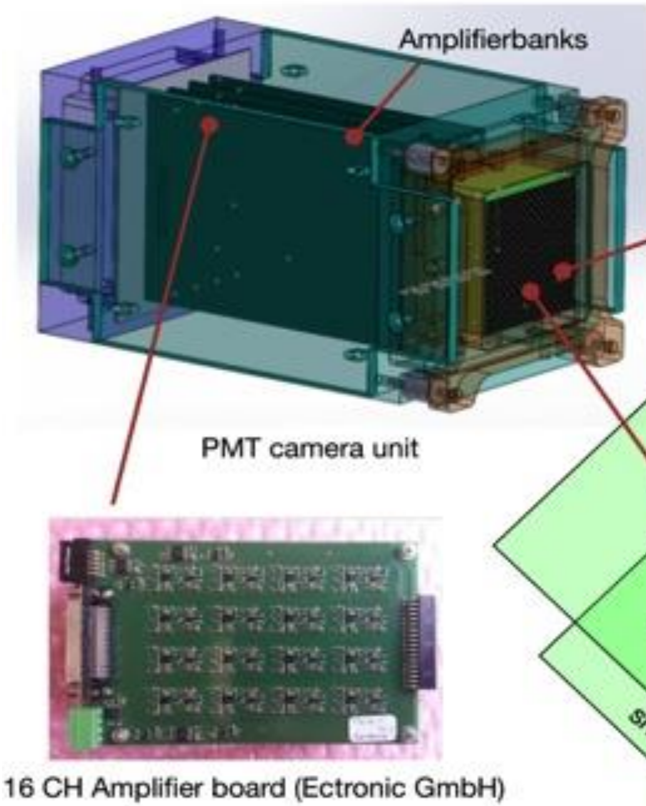


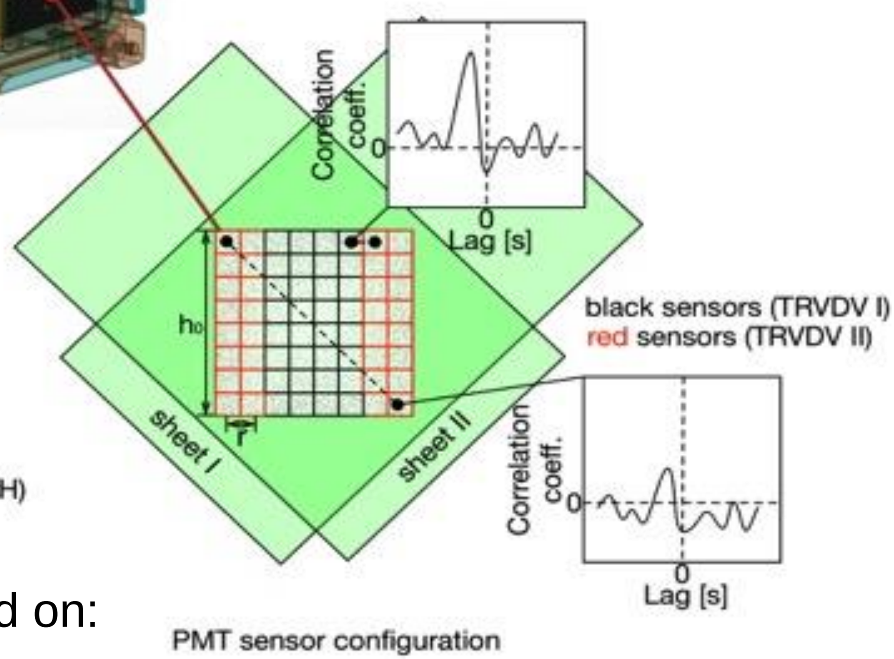


Ecker et al. (2015a,b,c)

- Multi-channel PMT cameras
- Convective velocities for heated supersonic jet
- Intermittency factor distribution
- Frequency dependent convective velocities

Key Development: PMT camera

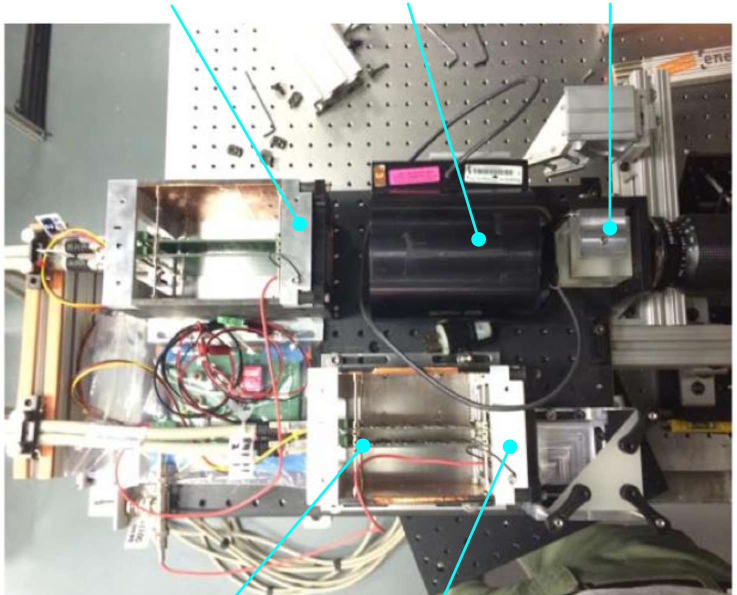


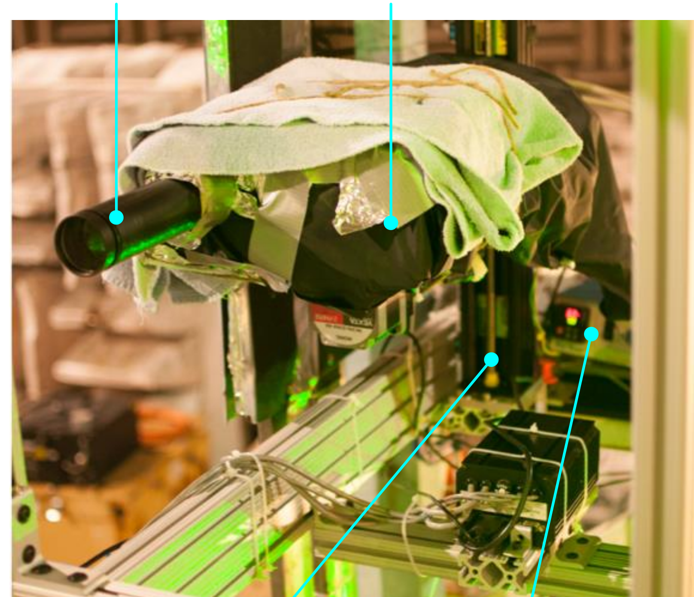


Newly developed PMT camera based on:

- Hamamatsu H8500C/H10660 64 CH PMT array
- Custom 16 CH instrument amplifier boards
- FPGA based DAQ backend allows recording at 50MHz sampling rate. Preprocessing on the FPGA reduces actual streaming bandwidth to 10MS/s per channel

Time-resolved Doppler Global Velocimetry



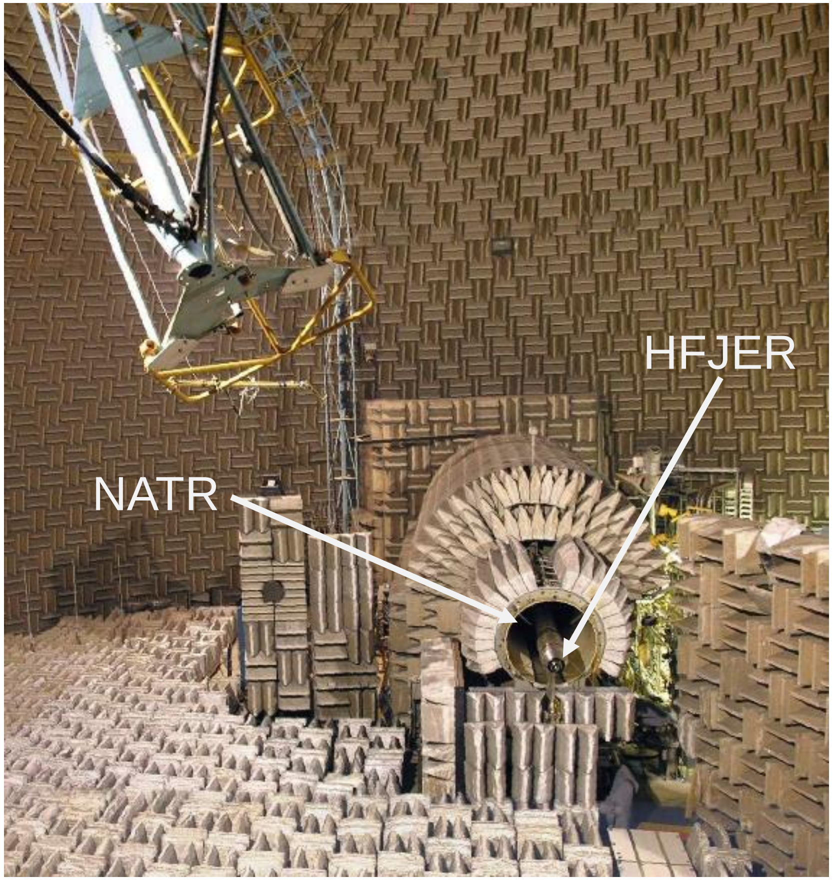


Lens focal length	200 mm
Magnification	1.257
Sensor area (effective)	24.12 x 48.7 mm^2
Measurement area	30.32 x 61.22 mm^2
(horizontal) spatial resolution on measurement plane	7.58 mm

- **250 kHz flow sampling**
- 3-velocity component capability
- 32-points simultaneously sampled

Facility

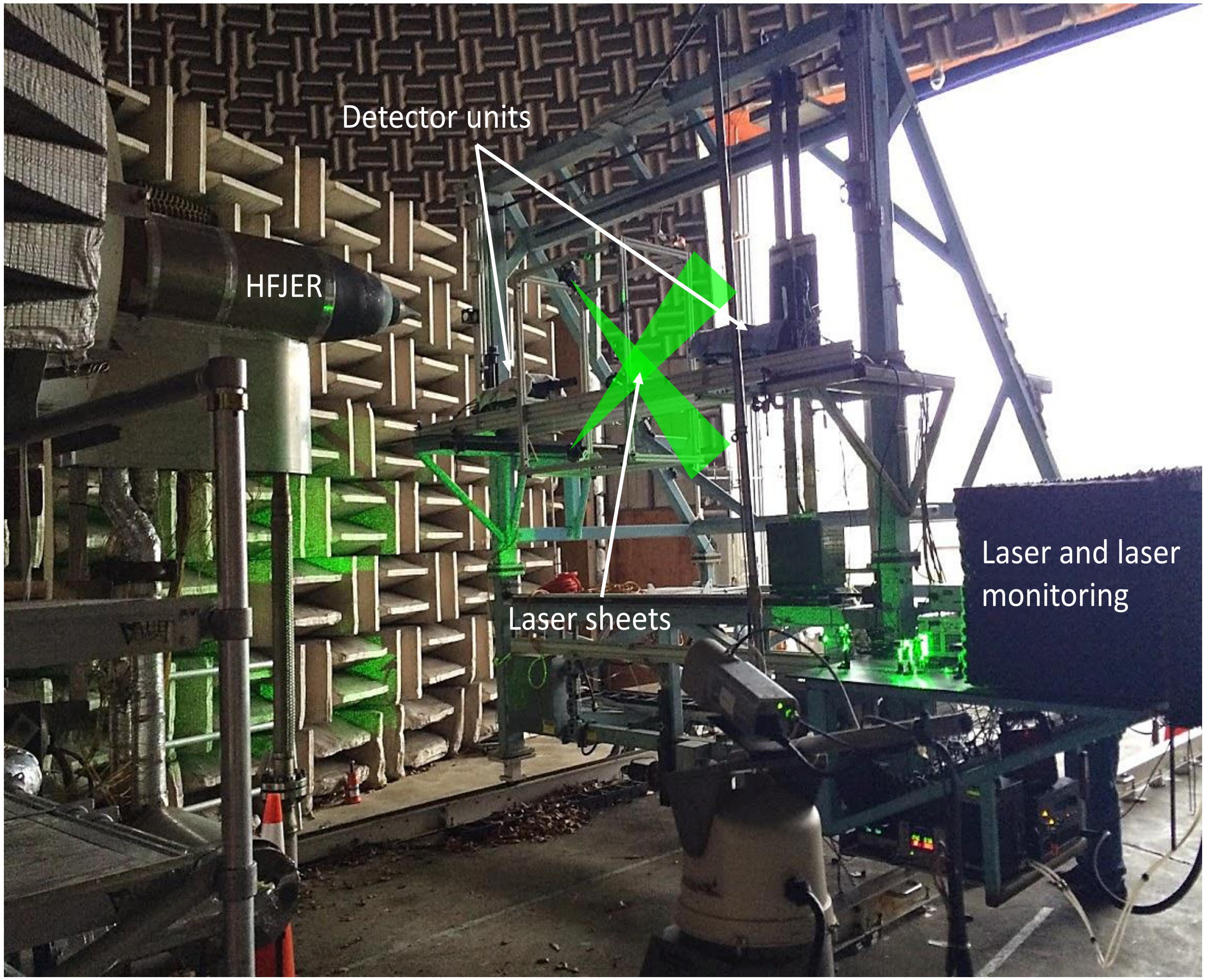
Tests in Nozzle Acoustics Test Rig (NATR) and High Flow Jet Exit Rig (HFJER) at the NASA GRC Aero-Acoustics Propulsion Laboratory



- 65 feet high, 130 feet diameter AAPL dome
    - Anechoic testing environment
    - Engine component R&D
- NATR:, 53 inch diameter, free-jet acoustic wind tunnel
- HFJER to mount test nozzle hardware within NATR

http://facilities.grc.nasa.gov/aapl/

Instrument arrangement in facility



Configuration instantaneous velocity uncertainty $\pm 9\ m/s$

Installation:

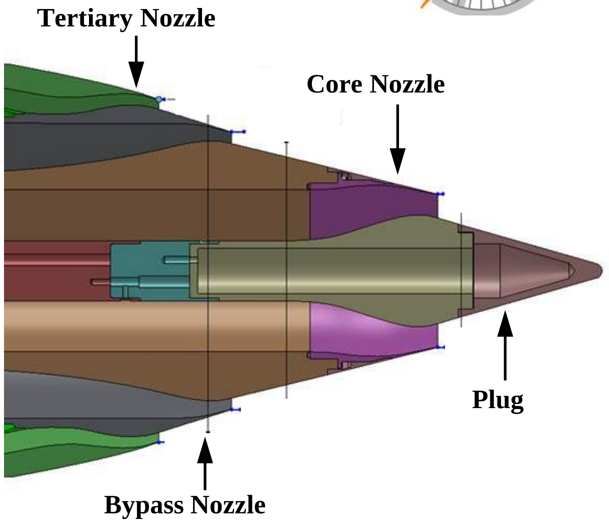
- Used NASA facility traverse
- All optics, electronics on traverse
- Acoustic box for acoustic and thermal shielding of Laser and reference gas cell

Notes:

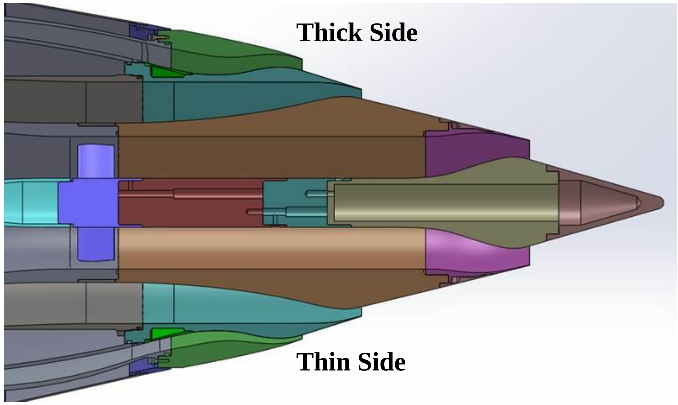
- Operation robust over $25^{o}C$ temperature changes (and freezing temps)
- More seeding than PIV
- Laser frequency stabilization

Three-stream experiments

Area ratio:	
A_t / A_c	1.0
A_b / A_c	2.5
Nozzle pressure ratio:	
NPR: core and bypass	1.8
NPR: tertiary	1.4
Nozzle temperature ratio:	
NTR: core	3.0



The axisymmetric-nozzle system used in the three-stream experiments.



The offset nozzle system used in the three-stream experiments.

0.156” offset

All experiments at 0 free jet Mach number

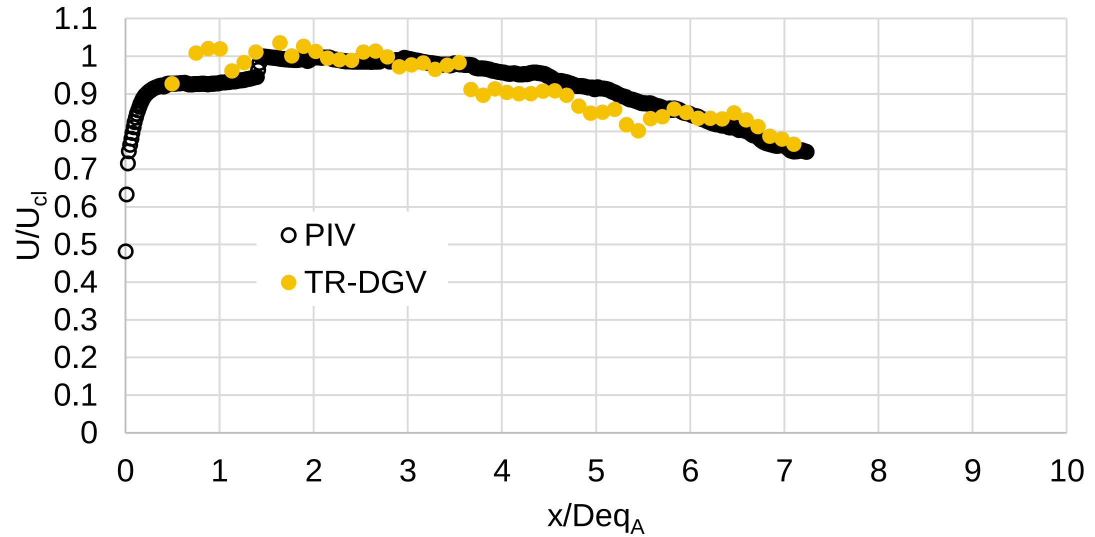
Flow seeding:

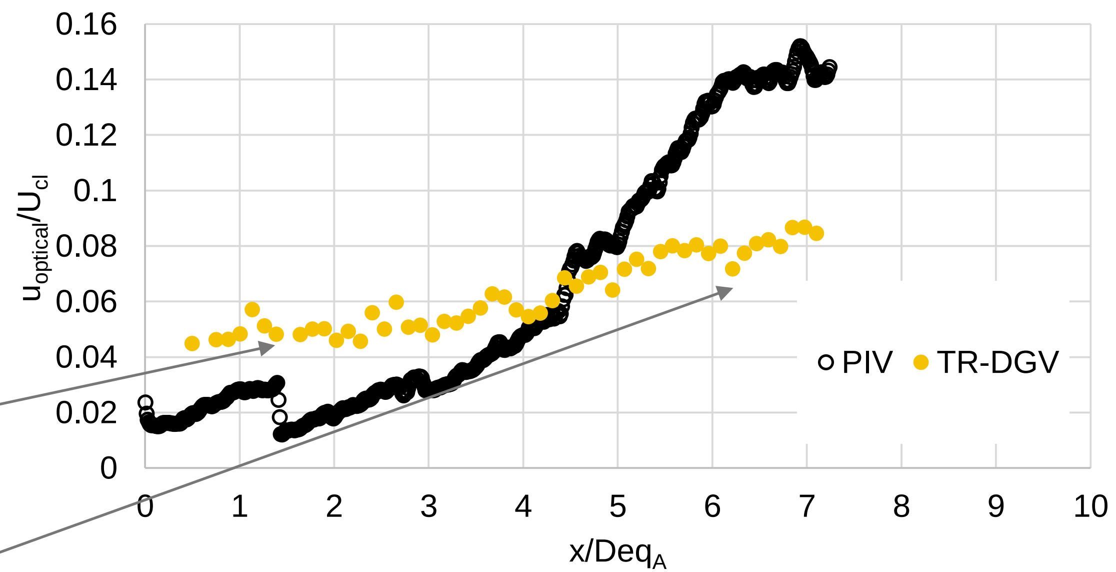
- 0.5 μm diameter alumina powder.
- Seeding colloid prepared using a pH stabilization technique (Wernet and Wernet 1994)

Velocity results: Validation

Comparison PIV data: Henderson and Wernet (2016)

- Laser frequency fluctuations
- Mean velocity comparison reasonable
- Turbulence results show some differences
  - Instrument variance
  - “Missing” samples

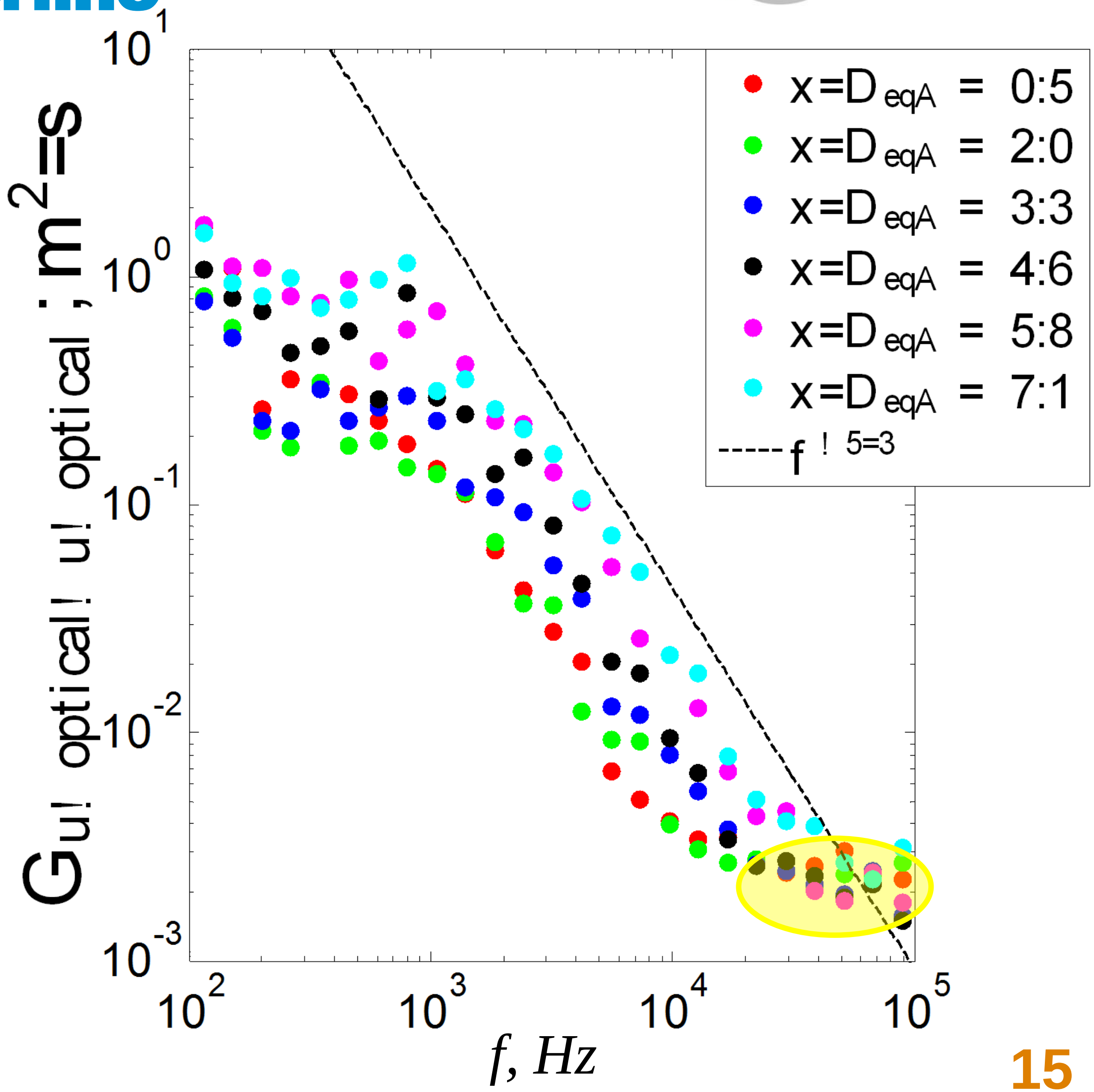




Velocity spectra: Axisymmetric nozzle on centerline

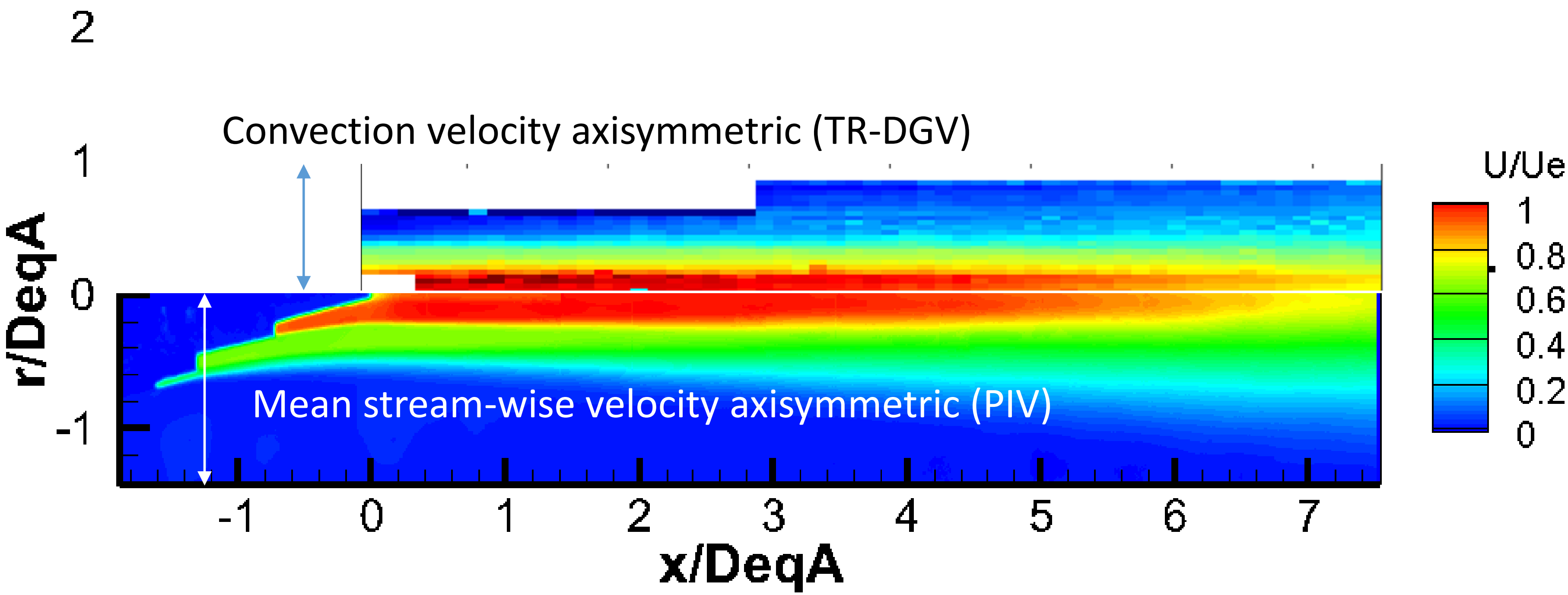
Stream-wise development of velocity spectra

- Consistent increase at all frequencies
- Spectral estimator important
  - Drop-out
  - Spectral variance
- Consistent instrumentation noise floor
- Spectral uncertainties still being quantified



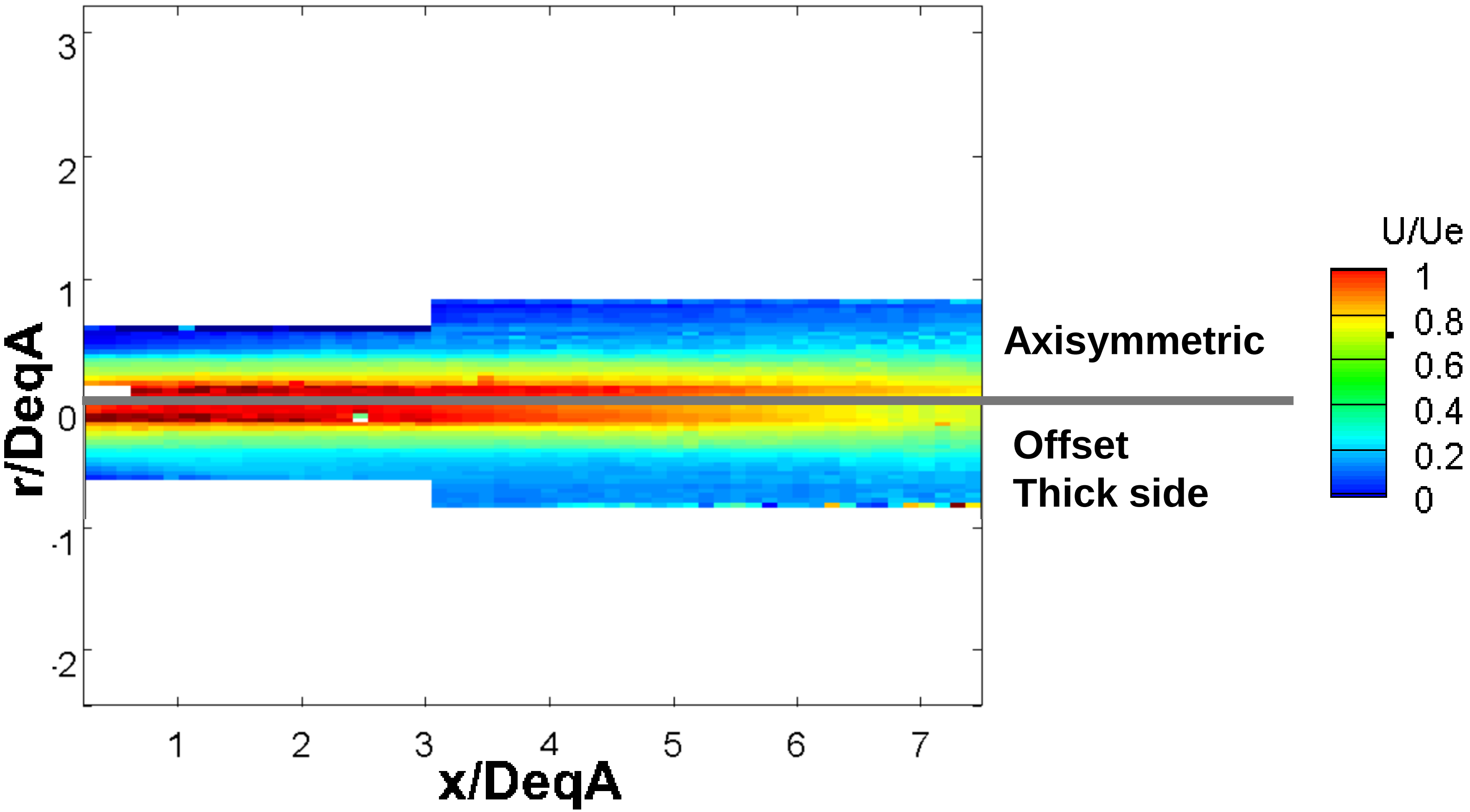
Convection velocity: Axisymmetric

Convection velocity from time/space correlation across stream-wise-spaced sensors (e.g., Ecker et al. AIAA J. 2015, $\pm 6.5\%$ RMS uncertainties)



Comparison of convection and mean velocity

Convection velocity: Axisymmetric vs Offset

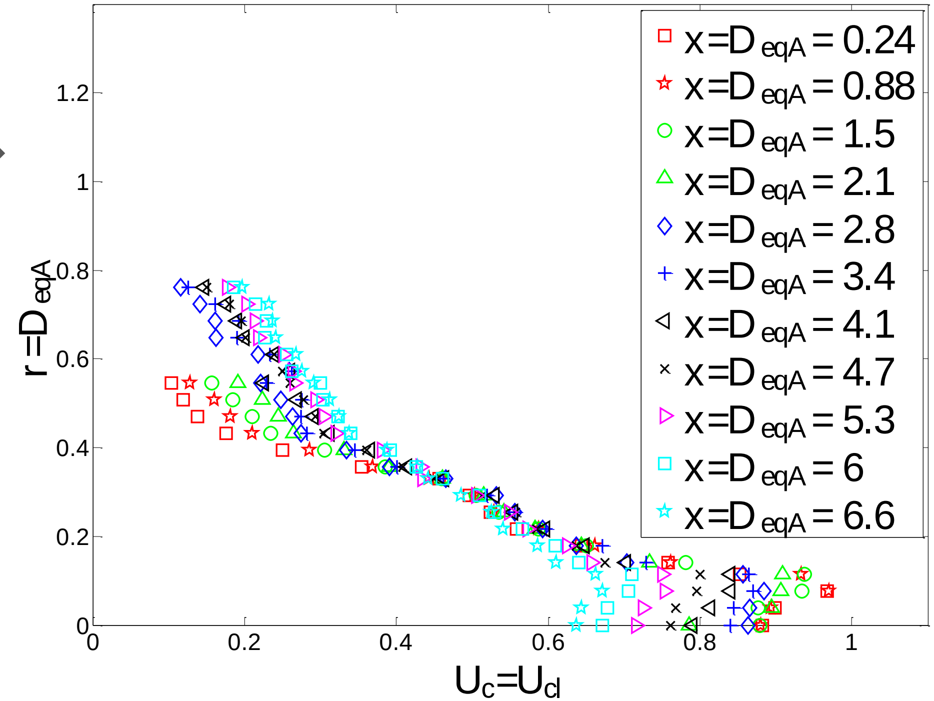


Offset clearly thickened for x/DeqA<3
Diminishes as flow develops

Convection velocity

Axisymmetric configuration

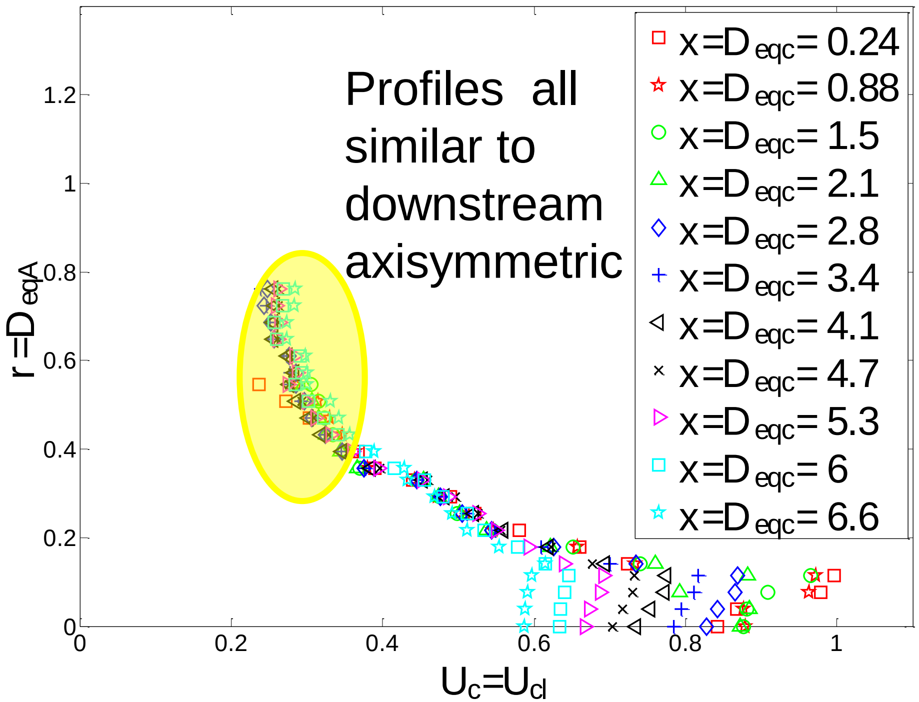
Development of profiles throughout this region



Offset configuration

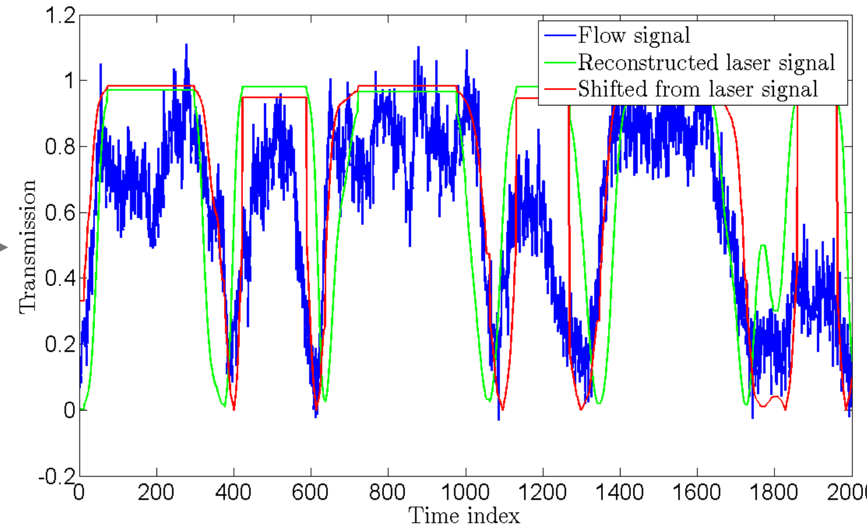
Virtually no change in profiles for outer portions of shear layer

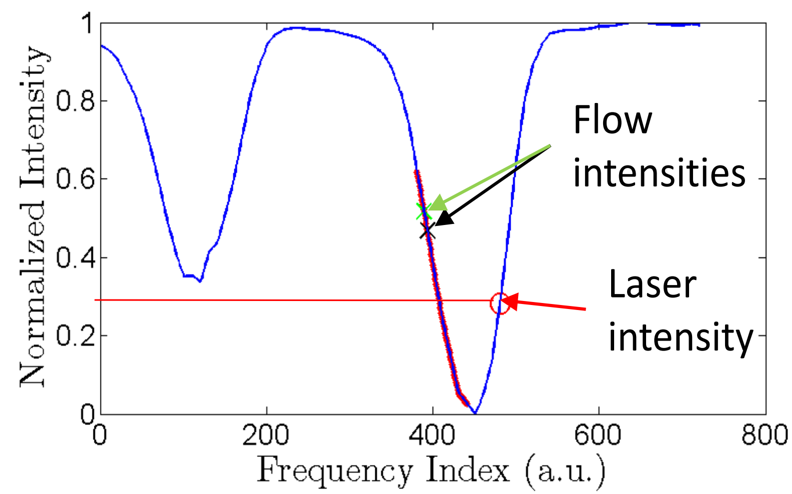
Profiles all similar to downstream axisymmetric



Regarding TR-DGV

- Discussed more instrumentation aspects in AIAA-2016-0029
- Laser frequency fluctuations
    - On-going work for signal processing
- Current results first for scaled-up arrangement
    - 250 kHz velocimetry
- Shows strength of method for time-resolved data
- Work confirms complementary role for TR-DGV in conjunction with PIV





Conclusions and next steps

- **Measurements using time-resolved velocimetry in 3-stream jet**
- **Good agreement of mean velocity data with PIV comparison data**
  - Turbulent intensity problematic due to noise influence, signal estimation
- **Used time-resolved data to begin analysis of statistical turbulence characteristics**
- **Next steps**
  - Continue refinement of velocity estimation
  - Use spectral and correlation data to update source models for three-stream jet predictions
  - Analyze physics using both PIV and TR-DGV insights
  - Process more data: two more configurations, one additional condition

Questions ?

Background

Review 3-stream work

NASA results previously reported

Turbulence information in 3-stream jet noise predictions

Henderson, Brenda. "Aeroacoustics of three-stream jets." *18th AIAA/CEAS Aeroacoustics Conference*, Colorado Springs, CO, 4-6 June, 2012, AIAA Paper 2012- 2159.

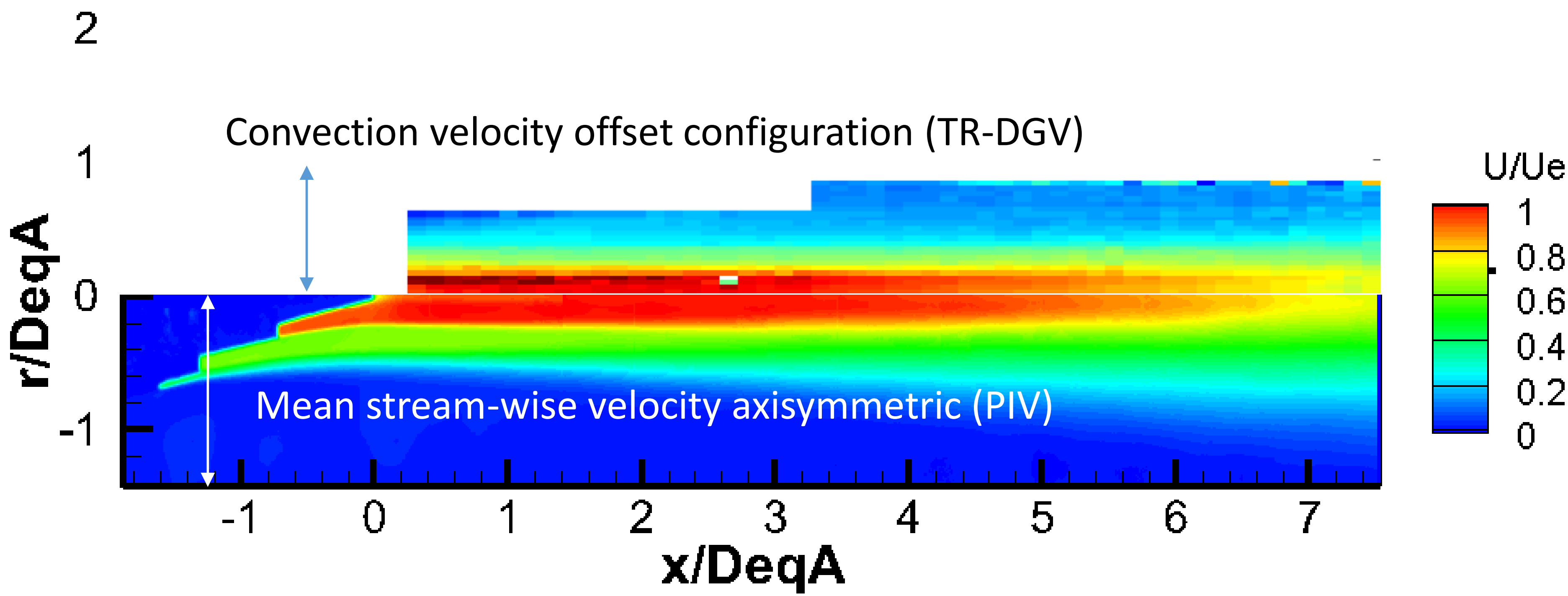
Papamoschou, D., Johnson, A. D., & Phong, V. Aeroacoustics of Three-Stream High-Speed Jets from Coaxial and Asymmetric Nozzles. *Journal of Propulsion and Power*, *30*(4), 2014, 1055-1069.

Simmons, S. P., Henderson, B., & Khavaran, A. “Flow Field and Acoustic Predictions for Three-Stream Jets,” *50th AIAA/ASME/SAE/ASEE Joint Propulsion Conf.*, Cleveland, OH, 2014.

Henderson B. S., Bridges J. and Wernet M.P., “Jet Noise Reduction Potential From Emerging Variable Cycle Technologies,” 48th Joint Propulsion Conference and Exhibit cosponsored by the AIAA, ASME, SAE, and ASE Atlanta, Georgia, July 30–August 1, 2012.

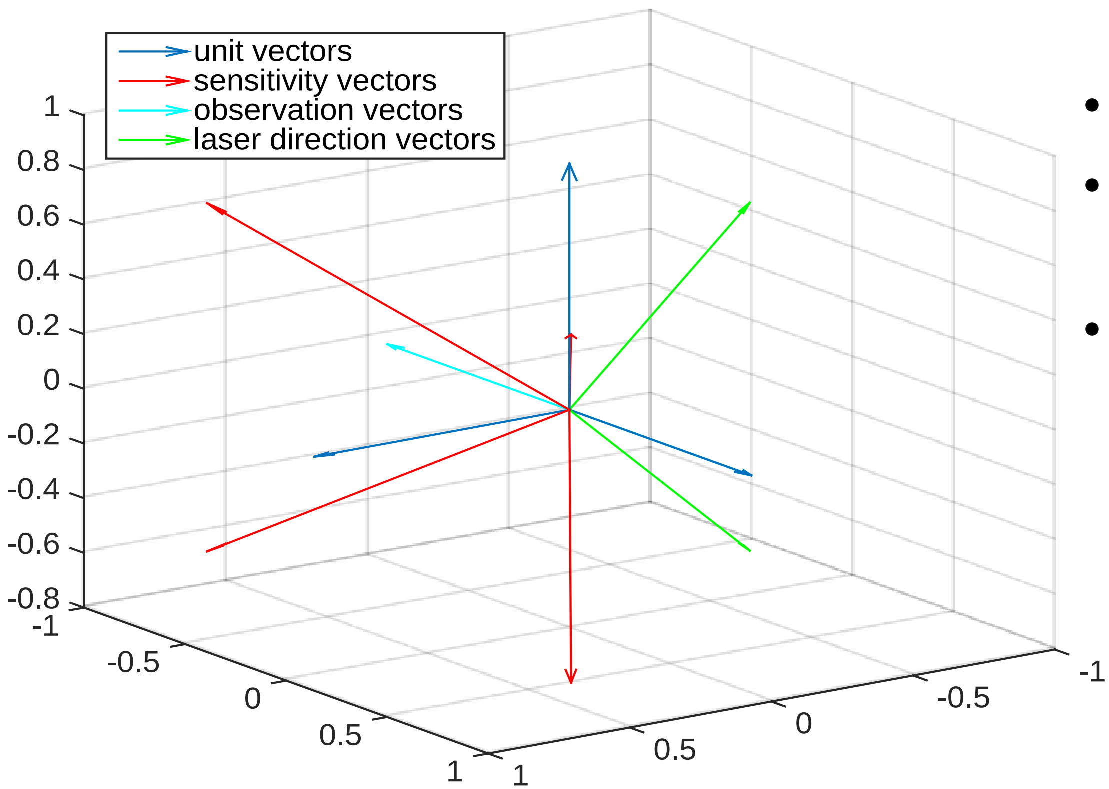
[19]Khavaran A. and Bridges J., “Jet Noise Scaling in Dual Stream Nozzles”, AIAA–2010–3968, 2010.

Convection velocity: Offset



Offset configuration convection velocity compared to mean velocity of axisymmetric case (reference)

TR-DGV geometry



- 45 deg. arrangement
- Uncertainty (inst) 9.2 /6.5 / 6.2 m/s
- Uncertainty (mean) 1.5 /1.5 /1.5 m/s

$$u_{optical} = -\frac{\sqrt{2}}{2}u + \frac{\sqrt{2}}{2}v + w$$

$$\delta u_i = \frac{c}{f_0}\sqrt{\left(\frac{df}{dT}\right)_i^2 (\delta T_i)^2 + T_i^2\left[\delta\left(\frac{df}{dT}\right)_i\right]^2 + \frac{f_i^2}{f_0^2}\left\{\left(\frac{df}{dT}\right)_0^2 (\delta T_0)^2 + T_0^2\left[\delta\left(\frac{df}{dT}\right)_0\right]^2\right\}} \quad (3)$$

$$\Delta\vec{U} = \begin{pmatrix}\delta \boldsymbol{u_x}\\ \delta \boldsymbol{u_y}\\ \delta \boldsymbol{u_z}\end{pmatrix} = \sqrt{\left(\begin{bmatrix}R_{11} & R_{12} & R_{13}\\ R_{21} & R_{22} & R_{23}\\ R_{31} & R_{32} & R_{33}\end{bmatrix}\right)^2 \begin{pmatrix}\delta u_1\\ \delta u_2\\ \delta u_3\end{pmatrix}^2 + \left(\begin{bmatrix}\delta R_{11} & \delta R_{12} & \delta R_{13}\\ \delta R_{21} & \delta R_{22} & \delta R_{23}\\ \delta R_{31} & \delta R_{32} & \delta R_{33}\end{bmatrix}\right)^2 \begin{pmatrix}u_1\\ u_2\\ u_3\end{pmatrix}^2} \quad (4)$$